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Development of Constructed Wetlands for the Reuse of Wastewater in Semi-Arid Regions

Case Study at Utah Test and Training Range

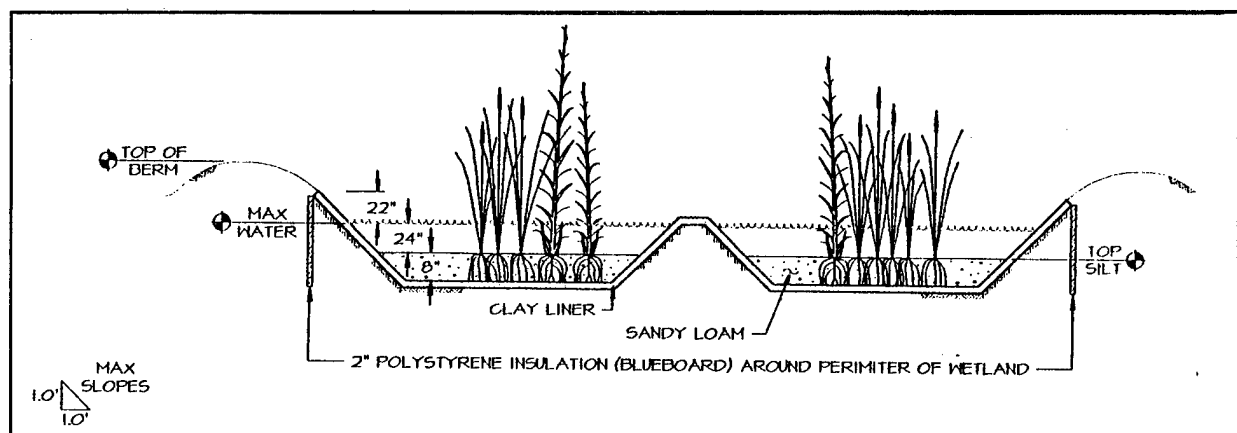
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Foreword

This study was conducted for Utah Test and Training Range, Hill Air Force Base, UT under Military Interdepartmental Purchase Request (MIPR) No. FD2020-9517750; Work Unit U65, "Wastewater Treatment Alternatives." The technical monitor was Patrick Sullivan, 00-ALC/EME.

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1 Introduction

Background

Hill Air Force Base (AFB) is located on the western desert of Utah, on the western side of the Great Salt Lake, about the same latitude as Salt Lake City, UT. The location typically experiences hot dry summers and cold winters. Hill AFB is responsible for the operation and maintenance of the Utah Test and Training Range (UTTR). The base contains wastewater treatment and disposal facilities, consisting of two infiltration ponds operated in parallel, followed by an emergency overflow basin that safeguards against unexpectedly high flow rates. The ponds function as rapid infiltration basins and all of the water applied is lost through evaporation or infiltration/percolation.

A previous evaluation done for the U.S. Air Force (Forsgren Associates, Inc. December 1994) concluded that the existing facilities should be replaced. This initial study considered several alternatives and a recommended construction of a lined, total containment lagoon for complete evaporation of the wastewater. (Details of these alternatives and descriptive information regarding the sewerage system at UTTR can be found in the Forsgren Associates report.) Since the Forsgren recommendation had a relatively high cost and included no possibility for beneficial water reuse, the Environmental Management Directorate at Hill AFB requested the U.S. Army Construction Engineering Research Laboratories (USACERL) to further evaluate the system and to suggest cost-effective, feasible alternatives not identified in the previous study.

Objectives

The objective of this study was to evaluate the design and function of the wastewater treatment and disposal facilities at the Utah Test and Training Range, Hill AFB, for possible applicability of USACERL's concept for the reuse of wastewater.

Approach

1. A literature search was done into pertinent Air Force documents and related authoritative information sources on constructed wetland technology.
2. A site visit was made to the UTTR to review and evaluate the wastewater treatment and disposal facilities, and to interview Hill AFB and UTTR personnel.
3. USACERL researchers also met with responsible officials in the State of Utah Department of Environmental Quality to discuss issues of environmental regulations relevant to the UTTR facility.
4. The collected information was evaluated, and a cost-effective process train was designed to augment the existing system with environmentally friendly technologies.

Scope

Although this project was specifically conducted for UTTR, the reuse concept can be applied to other U.S. Department of Defense installations.

Mode of Technology Transfer

The design, plans, and specifications for construction have been provided to Hill AFB; USACERL's wastewater reuse concept is planned for implementation at UTTR.

2 Conceptual Development

Wastewater Treatment Plant Data

The UTTR is in a unique setting. The facility is on the western side of the Great Salt Lake, approximately 50 miles west of Salt Lake City, UT. It is not only in the western desert and experiences the resulting arid climate, but because of the proximity to the Great Salt Lake is totally lacking normal potable water sources. The groundwater table is at least 160 feet below the ground surface and is saline; the base has no fresh surface water sources.

As a result, the saline groundwater is pumped to the surface, treated to potable water quality via reverse osmosis (RO) and distributed to the necessary buildings and activities in the built-up portion of the base. The spent brine from the RO operation is conveyed to a large containment pond where seepage and evaporation dispose of the water. Seepage to the groundwater is not an issue in this location because of the saline character of the aquifer. The wastewater from the habitations and activities at UTTR is collected and conveyed to the previously described rapid infiltration basins for disposal. The potential high quality of this treated wastewater, as compared with the original saline groundwater, makes consideration of beneficial reuse for wildlife habitat and landscape irrigation attractive. Treating the wastewater to acceptable reuse quality may be more economical than treating additional volumes of saline groundwater via RO for the same purpose.

The wastewater flow rate is not monitored or metered, but can be conservatively estimated from the actual water production records from the RO operation (Table 1). Based on the data in Table 1, the average present flow would be estimated as about 18,200 gallons

Table 1. Water production via reverse osmosis at UTTR, 1993-1995.

Month	Average Daily Production (gpd)
January	16,500
February	17,780
March	18,900
April	20,700
May	16,900
June	19,600
July	23,000
August	18,900
September	21,000
October	15,200
November	14,900
December	15,500
Average	18,200

per day (gpd).^{*} The future status of UTTR is undetermined, but for this evaluation, the possible maximum average future flow was assumed to be 37,000 gpd. However, it appears likely, based on discussion with local personnel, that the future flow will remain close to or even drop below the present rate. This study, therefore focused on use of a constructed wetland for treatment at the present flow rate. The impact of a future increase was considered, and the possible construction of a future expansion was also included in the assessment.

UTTR Technical and Operational Data

In preparing for this evaluation and design, Messrs. Reed and Andrews visited the UTTR site in August 1995. Discussions with site personnel and with appropriate officials from the State of Utah revealed several discrepancies within the 1994 Forsgren Associates report.

The Forsgren report states that the present rapid infiltration (RI) basin facility is "frequently overwhelmed by influent flow in excess of capacity." Discussions with the system operator in August 1995 indicated that the RI basins had not overflowed during his 14-year tenure on the job. Even if the basins do discharge, the final overflow basin would catch and infiltrate the spillage so there would be no uncontrolled discharge from the system. Visual observations during the August 1995 visit revealed no evidence of recent flow into this final overflow basin.

It is believed that the existing pair of RI basins has more than adequate capacity to infiltrate the entire present flow successfully. The existing basins also have several feet of unused freeboard; if the flow rate does increase in the future, the water level may rise, but this will expose additional sidewall surface for infiltration. It is not possible to predict the ultimate capacity of these two basins. However, the combined additional freeboard in the existing basins and the use of the existing overflow basin would provide more than adequate capacity for the possible future flow of 37,000 gpd.

The Forsgren report also states that the existing facilities "do not comply with regulatory requirements and do not protect groundwater resources, and were not constructed in accordance with any applicable criteria." The existing facilities function as rapid infiltration basins. Mr. Reed, the prime author of this report, helped the USEPA to develop criteria for the RI concept and authored a USEPA design manual on the topic (USEPA 1984). Examination of this *Process Design Manual* and more recent sources (Reed, Crites, and Middlebrooks 1995) indicates

^{*} 1 gal = 3.78 L.

that the RI basins at UTTR were constructed and are functioning acceptably. Protection of groundwater resources typically applies to fresh water aquifers, which have a potential for use as a drinking water aquifer. In those cases, pollution of the aquifer with nitrates, from any source, can have an adverse impact. At UTTR, the aquifer is saline and the reverse osmosis treatment effectively removes these dissolved contaminants so the present operations would have no impact.

Regulatory Data

During their August visit, Messrs. Reed and Andrews discussed the issue of regulatory compliance with State officials (Mr. Jay B. Pitkin, Manager, Engineering and Water Quality Management Branch; Mr. Larry J. Mize, Manager, Ground Water Protection Section; State of Utah, DEQ). In Utah, discharge to groundwater is governed by the *Administrative Rules for Ground Water Quality Protection*, R317-6, Utah Administrative Code (20 March 1995), and water reuse is covered by the *Water Reuse Rule*, R317-1-4, "Utilization and Isolation of Domestic Wastewater Treatment Works Effluent" (20 January 1995). It was indicated that the UTTR facilities do not have a discharge permit and do not need one, since the system does not discharge to surface waters. The present practice of allowing RI basins to percolate to the deep groundwater is completely acceptable to the State of Utah because of the saline character of the aquifer and the remote location of the base. Consequently, the current use of RI basins at UTTR does not need to be changed for any regulatory reason.

UTTR Wastewater Treatment Plant Upgrade Concept

These discussions and observations revealed no technical or regulatory justification for modifying the existing infiltration basin system. Contrary to the recommendations of the Forsgren report, the "No Action" option is completely acceptable, and the most economical choice. If the future flow ever increases to the rate of 37,000 gpd and the existing three-basin complex proves inadequate, it would be a simple matter to excavate a fourth basin with locally available equipment.

The only reason to modify the existing system is to take advantage of the reuse potential for the water. The reuse options include an enhanced wildlife habitat based on a wetland with an open pond, and/or landscape irrigation in the built-up portion of the UTTR complex. If the first option were incorporated as part of the final disposal near the existing basins, the plan would probably not require approval by the State, except for a construction permit for the treatment wetland since

human exposure and contact would be negligible. However, the second option, using landscape irrigation close to the habitations and other related activities, is more complex, and would, according to the State, require additional treatment and permitting. They would consider such an irrigation operation a Type 1 reuse activity with human exposure to be likely, and would require filtration, disinfection, and regular monitoring. These additional treatments and monitoring would significantly increase the cost and complexity of this reuse option. Water quality requirements for Type 1 reuse are:

- biological oxygen demand (BOD) 10 mg/L
- turbidity 2 NTU
- fecal coliforms, 14/100 ml (weekly)
- residual Cl 1 mg/L.

However, there are no habitations, routine human activity, or human exposure in the vicinity of the existing RI basins. Consequently, the addition of a treatment and wildlife habitat wetland at this site should not be subject to the Type 1 requirements.

Either of these reuse options will require at least a partial sealing of the existing RI basins. This would prevent infiltration of the entire flow and induce a pond discharge that can be treated and either beneficially reused and/or disposed of to the ground. The envisioned concept would seal the two existing RI basins with bentonite. The new discharge would then flow to a constructed wetland for further treatment. The discharge from this wetland could be diverted via a pump station for return to the built-up portion of UTTR for landscape irrigation. (The additional filtration, disinfection, storage, and monitoring facilities would be at the built-up portion of the base.)

The main discharge pathway from the treatment wetland would be to the existing overflow basin. This basin would be modified by excavating a deeper pond near the center, and partially treating some of the bottom with bentonite to increase the basin's water retention capacity. Infiltration and percolation through the bottom and side walls of this existing basin would provide final disposal of the wastewater as is now accomplished by the two RI basins. Both the constructed treatment wetland and the bottom of the modified overflow basin would be planted with emergent wetland vegetation species and would serve to provide significant wildlife habitat values before final disposal of the wastewater. The treatment wetland would be designed to provide very low levels of BOD and total suspended solids (TSS) during the summer irrigation season in case the optional landscape irrigation pathway is selected.

3 Constructed Wetlands for Wastewater Treatment

The use of wetlands for waste treatment has increased exponentially since the 1980s. These applications are used to treat municipal, domestic, industrial, and commercial wastewater, landfill leachates, agricultural wastes, stormwater runoff, mine drainage, and combined sewer overflows. Wetlands are desirable for these purposes since they are typically inexpensive to build, easy to operate, and capable of very effective treatment.

Wetlands are defined as land where the water surface is near the ground surface long enough each year to maintain saturated soil conditions along with the related vegetation. Marshes, bogs, and swamps are all examples of naturally occurring wetlands. A "constructed wetland" is a wetland specifically constructed for pollution control and waste management, at a location other than existing natural wetlands. Most treatment wetlands placed in service during the past decade are constructed wetlands. Although the constructed wetland technology has gained popularity in the United States, there is limited guidance on design and operation of constructed wetland. Useful references in relation to this UTTR project include the USEPA's *Process Design Manual for Land Treatment, Supplement on Rapid Infiltration and Overland Flow* (1984), *Wastewater Treatment/Disposal for Small Communities* (1992), *Guidelines for Water Reuse* (1992), and *Constructed Wetlands and Aquatic Plant Systems for Municipal Wastewater Treatment* (1988), and the European Community/European Water Control Association's *Use of Constructed Wetlands in Water Pollution Control* (1990). This project used the *Natural Systems for Waste Management and Treatment* (Reed, Crites, and Middlebrooks 1995) as a main reference.

The two basic types of constructed wetlands are the free water surface (FWS) wetland and the subsurface flow (SF) wetland. Both types use emergent aquatic vegetation and are similar in appearance to a marsh.

The free water surface wetland typically consists of a basin or channels with some type of barrier to prevent seepage, soil to support the roots of the emergent vegetation, and water at a relatively shallow depth flowing through the system. The

water surface here is exposed to the atmosphere, and the intended flow path through the system is horizontal.

The subsurface flow wetland also consists of a basin or channel with a barrier to prevent seepage, but the bed then contains a suitable depth of porous media. Rock or gravel are the most commonly used media types in the United States. The media also supports the root structure of the emergent vegetation. The design of these systems assumes that the water level in the bed will remain below the top of the rock or gravel media. The flow path through the operational systems in the United States is horizontal.

The SF type of wetland has several advantages over the FWS type. If the water surface is maintained below the media surface, there is little risk of odors, public exposure, or mosquitoes. In addition, it is believed that the media provides greater available surface area for treatment than the FWS concept. As a result, the treatment responses are faster for the SF type and therefore it can be smaller in area than an FWS system designed for the same wastewater conditions. The subsurface position of the water and the accumulated plant debris on the surface of the SF bed offer greater thermal protection in cold climates than surface conditions of the FWS type.

These potential advantages are offset by the significant additional cost for procuring, delivering, and placing the gravel or rock media in the SF bed. The selection of the most appropriate concept will depend on site conditions, operational requirements, and the local costs for the media and for the land involved. In situations where public access, odors, or vectors are a critical issue, the SF type may be preferred despite cost. When the system can be at a remote site where these issues are of lesser concern, the FWS system can typically be constructed for a lower cost. A further advantage for the FWS type is improved habitat values since the water surface is exposed and accessible to birds and animals.

Some systems in Europe that treat domestic or municipal effluents accept untreated wastewater and typically have an inlet zone dedicated to solids separation. Most constructed wetland systems in the United States have some form of preliminary treatment prior to the wetland component. This ranges from septic or Imhoff tanks for small services, to primary treatment, lagoons, and full-scale biological secondary treatments such as activated sludge, trickling filters, oxidation ditches, etc.

Functional Components in the Wetland

The biological components in the wetland system with significant potential for wastewater renovation include vegetation and microbial organisms, either suspended in the water or attached to the surfaces of the media (in SF systems), or the submerged plant parts (in FWS systems).

The vegetation in the wetland may be a major system component, but one that plays a minor role in the direct renovation of the wastewater. Plant uptake of nutrients and other pollutants does occur, but most of these materials return to the water due to the annual senescence and decomposition of the emergent plant parts. For example, several studies have shown that a single harvest of the plants will account for less than 10 percent of the nitrogen removed by the wetland. Multiple harvests might improve permanent removal via the plants, but that activity would then disrupt operations and increase costs. The major role of the vegetation in these systems is simply its physical presence. The dense canopy shades the surface and prevents algae growth in the FWS type, and the root zone in the SF type is the source of oxygen for essential aerobic reactions. The roots and the submerged plant parts are the substrates for microbial growth.

The most active renovative components in the wetland system are believed to be the microbial organisms, and of these, the attached growth types are the most significant contributors. These attached growth organisms occupy the surfaces of the media and the roots in the SF system, and the submerged plant parts and benthic materials in the FWS concept. In effect, both types of constructed wetlands function as attached growth reactors with similar reactions and responses to those observed in trickling filters, and other conventional treatment concepts. The presence of greater available surface area in the SF wetland as compared to the FWS is responsible for the higher rates of treatment observed in the SF case.

These natural biological reactions are, in the general case, allowed to proceed at their "natural" rates without enhancement or stimulation via aeration, mixing, recirculation, or need for sludge management. In effect, these constructed wetland concepts trade time and space (i.e., detention time and land area) for energy-intensive operation and maintenance requirements. A treatment occurring in a few hours in an activated sludge process may require several days in a constructed wetland. In locations where suitable land is available at a reasonable cost, the economics will tend to favor the constructed wetland process. These wetlands are also more robust and more forgiving of upsets occurring in the preliminary processes as compared with more finely tuned and intensive mechanical systems such as activated sludge.

The major nitrogen removal pathway in these wetlands is microbiological. The pathway includes mineralization of organic N and release of ammonia, nitrification of ammonia, and finally denitrification of the resulting nitrates. In a system where all of the necessary components and support elements are available, nitrogen removal can be very effective. The critical step seems to be the nitrification reaction and, in some operating constructed wetlands, this step appears to be limited due to oxygen deficiencies in the system. In the FWS, the major source of oxygen is atmospheric reaeration at the exposed water surface. This source can be reduced in a wetland as compared with a pond since the wetland vegetation suppresses wind action, and floating plants, such as duckweed, can effectively seal the water surface. The lower depths in the FWS wetland are typically anaerobic.

The emergent wetland plants used in these systems can transmit air and oxygen to their root systems. This capability has evolved since these plant roots grow in an anoxic environment and would die without some oxygen source. It is believed that the oxygen level responds to the stress level at the roots, but is limited so very high organic loadings can exceed that capacity. The plant would then die. This oxygen does not diffuse into the soil or the gravel matrix, and so converts the surroundings into an effervescent aerobic environment. This oxygen is believed to be only available on the surfaces of the roots. As a result, microsites on these roots are believed capable of supporting aerobic organisms. When the organic loading is low enough, these aerobic microsites may be dominated by nitrifying organisms. When wastewater contacts such a microsite, nitrification can occur followed by denitrification in the largely anoxic environment in the SF bed. Since this oxygen does not diffuse from the roots, it is probably not available to the flowing wastewater in an FWS wetland.

Physical and chemical responses also play an important role in constructed wetlands. Sedimentation and filtration account for removal of a large portion of the BOD and TSS in the front part of the wetland bed. Volatilization of ammonia and susceptible organics can also occur during the relatively long detention times. Precipitation and complexation reactions effectively remove most metals and similar substances. Many refractory organic compounds can also respond favorably due to the generally anoxic conditions and the longer detention times. Adsorption and ion exchange reactions can also occur, but unless another mechanism releases or converts the adsorbed substance, these retention sites may be exhausted soon after the system is put into operation.

Performance Expectations

Parameters of concern in wastewater treatment systems may include: BOD, TSS, fecal coliforms, nitrogen, phosphorus, metals, and trace organics. Actual performance data for each of these are briefly summarized below.

BOD Removal

Effluent concentrations of less than 20 mg/L can easily be achieved in a few days detention time or less, despite the input concentration within the range of 30 to 250 mg/L. Figure 1 illustrates this fact with data from a SF wetland system serving a small community at Hardin, KY.

Preliminary treatment is provided by an erratically performing contact stabilization plant, with a design flow of about 0.1 million gallons per day (mgd). The wetland component consists of two parallel, identically sized, gravel bed cells; one supports a growth of *Phragmites* (common reeds), the other has *Scirpus* (bulrush). Because of differences in flow distribution, the detention time ("hydraulic residence time," or HRT) in the *Phragmites* cell is about 3.3 days, and 4.2 days in the *Scirpus* cell.

The vertical scale on the figure is logarithmic so all of the data may be seen conveniently. Over the period shown, the wetland influent BOD ranged from a low of 8 to almost 500 mg/L, primarily due to sludge losses from the contact stabilization

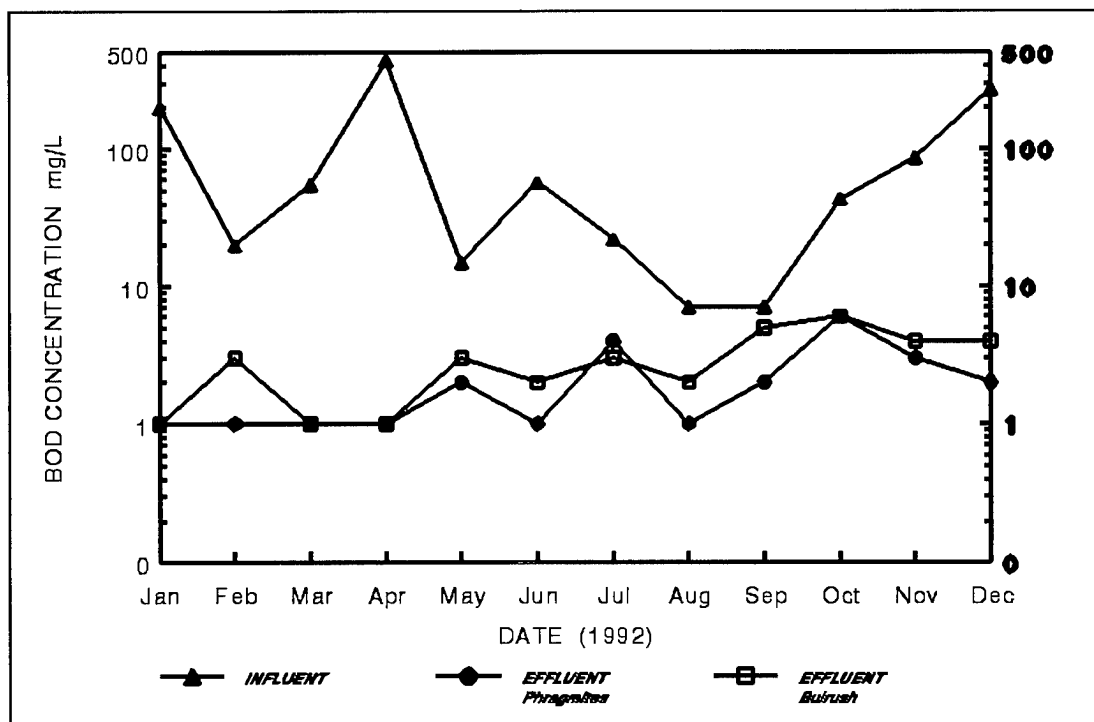


Figure 1. BOD removal in a constructed wetland.

plant. In spite of these wide excursions, the effluent BOD from both cells consistently remained below 6 mg/L throughout the period. Similar results have been observed from other systems; this response is a strong indication of the robust character of constructed wetlands. The Hardin data indicate that the *Phragmites* cell generally performed better than the *Scirpus* cell although the HRT was almost 1 day less on the *Phragmites* side. This may be due to an enhanced oxygen supply from the more extensive *Phragmites* roots.

Both SF and FWS types of wetland systems are unique compared with other forms of wastewater treatment in that BOD is produced within the system due to the decomposition of plant litter and other natural organic materials. As a result, these systems can never achieve complete BOD removal, and a residual of 2 to 7 mg/L is typically present in the final effluent. A seasonal difference in BOD removal is not observed for this system in western Kentucky, but is apparent in colder climates. The 3- to 4-day HRT provided in this Kentucky system is enough to compensate for the reduced reaction rates at their winter temperatures.

TSS Removal

The TSS removal for the same Kentucky system discussed above for an 11-month period is shown in Figure 2. The vertical scale on the Figure is again logarithmic so that all data may be displayed. The TSS of the wetland influent varied from

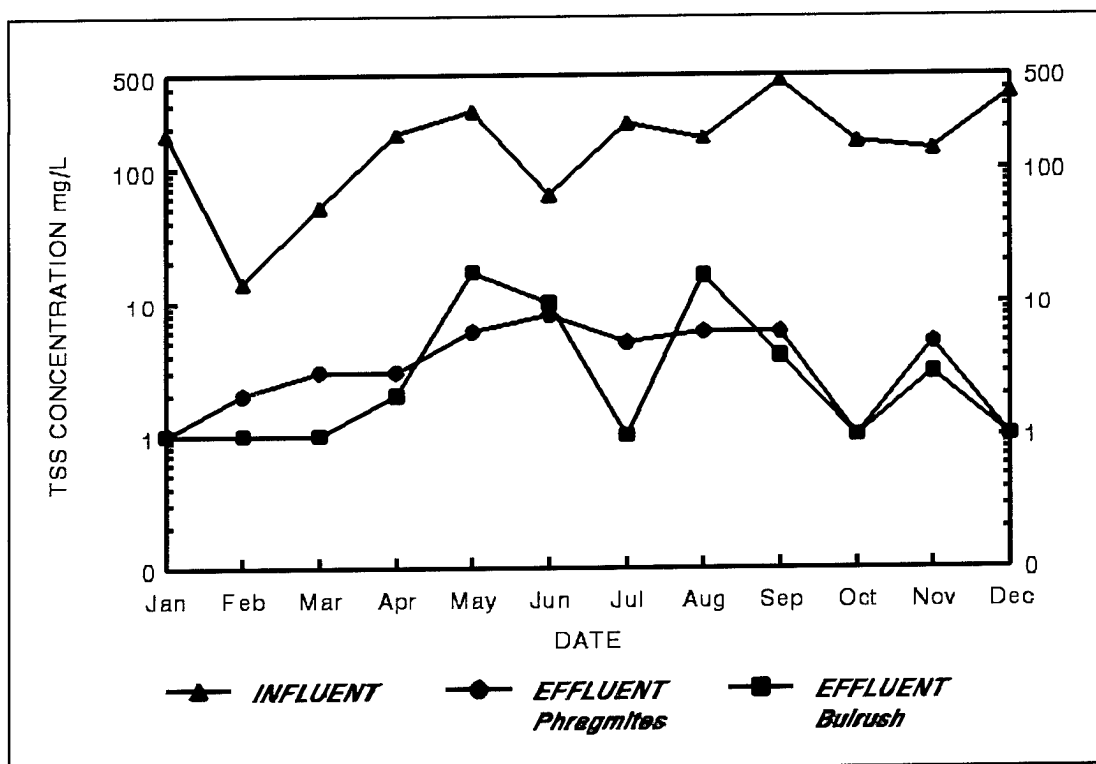


Figure 2. Constructed wetland influent and effluent TSS.

about 10 to 500 mg/L over the period of record. Again, in spite of these excursions, the effluent was generally below 10 mg/L for the entire period. No consistent difference in performance between the two cells were seen and none should be expected because the removal of TSS is a physical response and should not be related to the plant species used. The inorganic residues from the TSS will accumulate in the wetland bed over the long term. This is more critical in the SF concept since the water flows in the void spaces in the media. Based on experience, detrimental clogging of these systems is not expected during the design life of the facility if it is properly operated.

Pathogen Removal

Pathogen removal in both FWS and SF wetlands can be very effective (Table 2). Figure 3 shows the monthly data for the Kentucky system. The influent fecal coli ranged up to 500,000/100 ml; at times the effluent was as low as 10/100 ml. Here, the *Scirpus* cell showed generally better performance, probably because of the additional day of detention time provided in this cell.

As a rule of thumb, it can be expected that these wetland systems can achieve a one to two log reduction in fecal coliforms with an HRT of at least 3 days. In some cases, this may not be sufficient where stringent discharge limits prevail. The clarity of the wetland effluent permits the effective use of UV disinfection and many operational systems now employ this procedure. A specific design model for the removal

Table 2. Pathogen removal in SF and FWS wetlands.

Location	Type	HRT (d)	Organism	Concentration (#/100 ml)	
				In	Out
Santee, CA	SF	6	Total Coli Virus	10^7 10^3	10^2 10^1
Arcata, CA	FWS	5	Fecal Coli	10^3	10^1
Benton, KY	SF	3	Fecal Coli	10^5	10^2
Listowel, ONT	FWS	7	Fecal Coli	10^5	10^2
Bear Creek, AL	SF	4	Fecal Coli	10^5	10^1
Port Perry, ONT	FWS	7	Fecal Coli Fecal Strep. Pseudomonas	10^4 10^3 78	10^3 10^3 5
Hardin, KY	SF	4	Fecal Coli	10^5	10^2
Source: Reed, Crites, and Middlebrooks (1995).					

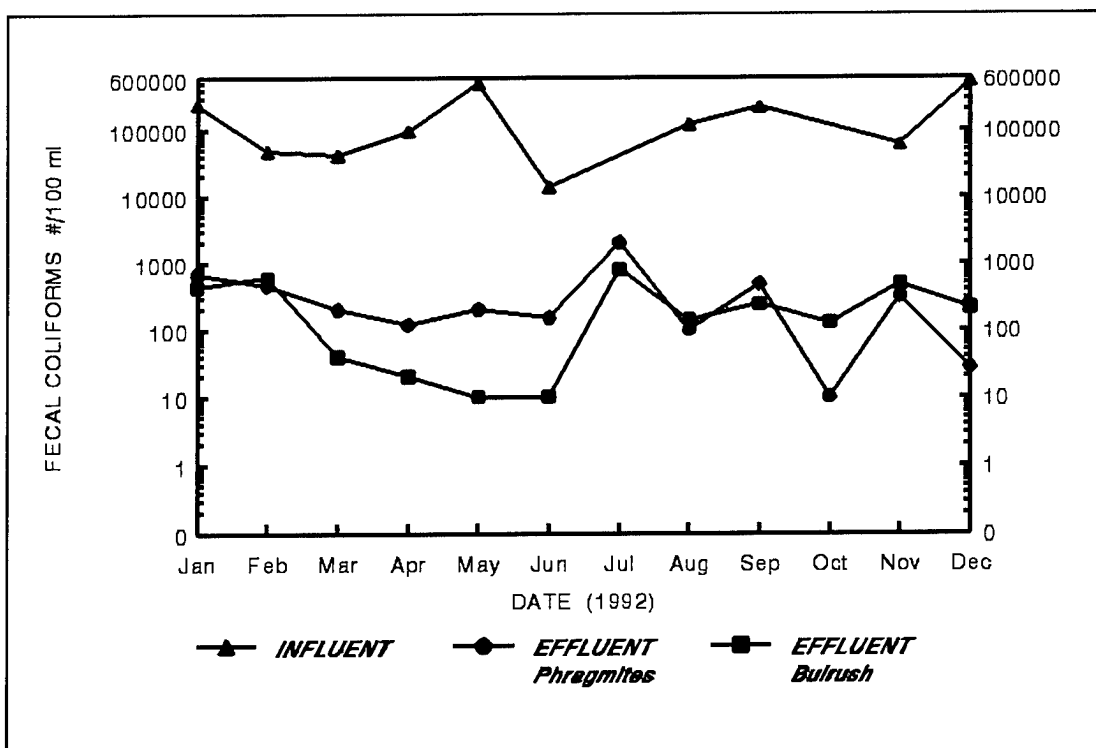


Figure 3. Fecal coliform removal in constructed wetlands.

of pathogens in these wetland systems is not available. A conservative approach is to use a relationship developed for facultative ponds:

$$C_e/C_o = 1/[1 + t(K_T)]^n \quad [\text{Eq 1}]$$

Where:

$$K_T = 2.6(1.19)^{(T - 20)}$$

n = number of cells in series

t = detention time in the cell.

Phosphorus Removal

Phosphorus removal is somewhat limited in both types of constructed wetlands due to the limited contact with the soil and oxides of iron and aluminum. Removal is dependent on the detention time in the system and generally ranges from 30 to 50 percent. Additional removal will occur in the soil when in-ground disposal is the intended discharge pathway.

Metals Removal

Constructed wetland systems can remove metals very effectively. In this case, the processes are believed to be precipitation and complexation reactions, which should be equally effective in both SF and FWS systems. Figure 4 shows metals removal for two SF systems. The Santee system, with its longer HRT, achieved almost 100 percent removal for the parameters measured. The Hardin system achieved nearly the same results with only a 4-day HRT for copper and zinc. Both systems were treating municipal wastewater, but the metal concentrations in the wetland influents should be comparable to many industrial systems using biological treatment as a preliminary step (Reed, Crites, and Middlebrooks 1995).

Organic Priority Pollutant Removal

Table 3 lists removal of many organic priority pollutants in constructed wetlands. These data were obtained in pilot scale studies, but should be achievable in full scale systems as well. Loss to the atmosphere of the more volatile organics is an obvious pathway during the relatively long HRT in these systems. The generally anoxic environment will also help in the breakdown and removal of the more resistant refractory organics. High concentrations of these materials may be toxic to the plants and organisms in the wetland systems. Neutralization and/or partial removal in preliminary anaerobic reactors will typically be necessary for very high concentrations of these materials.

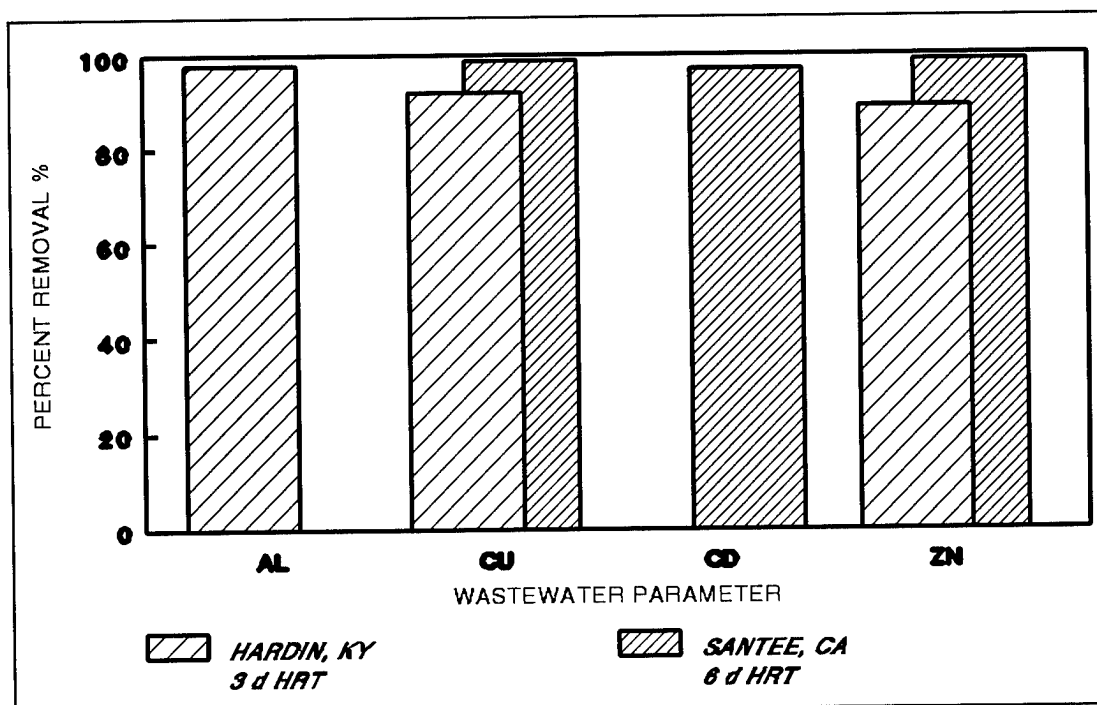


Figure 4. Removal of metals in constructed wetlands.

Nitrogen Removal

The nitrogen entering wetland systems can be a combination of organic nitrogen, ammonia (the combination expressed as TKN), and nitrate. Septic tanks, primary treatment systems, and facultative lagoon effluents do not usually contain nitrate but can have significant levels of organic N and ammonia. During the warm summer months, facultative lagoons can have low levels of ammonia in the effluent, but often contain high concentrations of organic N associated with the algae leaving with the effluent. Aerated secondary treatment system effluents typically have low levels of organic N but contain significant concentrations of ammonia and nitrate. Systems with high intensity or long-term aeration can have most of the nitrogen in the nitrate form.

Table 3. Removal of organic priority pollutants in constructed wetlands.

Compound*	Initial Concentration (mg/L)	Removal in 24 hrs(%)
Benzene	721	81
Biphenyl	821	96
Chlorobenzene	531	81
Dimethyl-phthalate	1033	81
Ethylbenzene	430	88
Naphthalene	707	90
p-nitrotoluene	986	99
Toluene	591	88
p-Xylene	398	82
Bromoform	641	93
Chloroform	838	69
1,2-Dichloro-ethane	822	49
Tetrachloro-ethylene	457	75
1,1,1-Trichloroethane	756	68
* Source: Reed, Crites, and Middlebrooks (1995).		

Figure 5 presents influent and effluent total nitrogen concentrations for an SF constructed wetland in Kentucky. The influent ranged from less than 10 to more than 40 mg/L; the effluent was near or below 10 mg/L for the period of record. The data shows somewhat better performance for the *Phragmites* cell, although the HRT in that cell (3.3 days) was about 1 day less than the parallel *Scirpus* cell. This is probably due to the more extensive root system for the *Phragmites* plants and the consequent greater availability of oxygen for nitrification of the ammonia.

Nitrogen removal in these wetland systems is strongly dependent on the temperature in the system. The results shown in Figure 5 for the system in Kentucky do not show a significant response to winter conditions, but more northerly locations will. Systems designed by the senior author of this paper in northwestern Canada use the wetland during the warm months and the partially treated wastewater is stored in

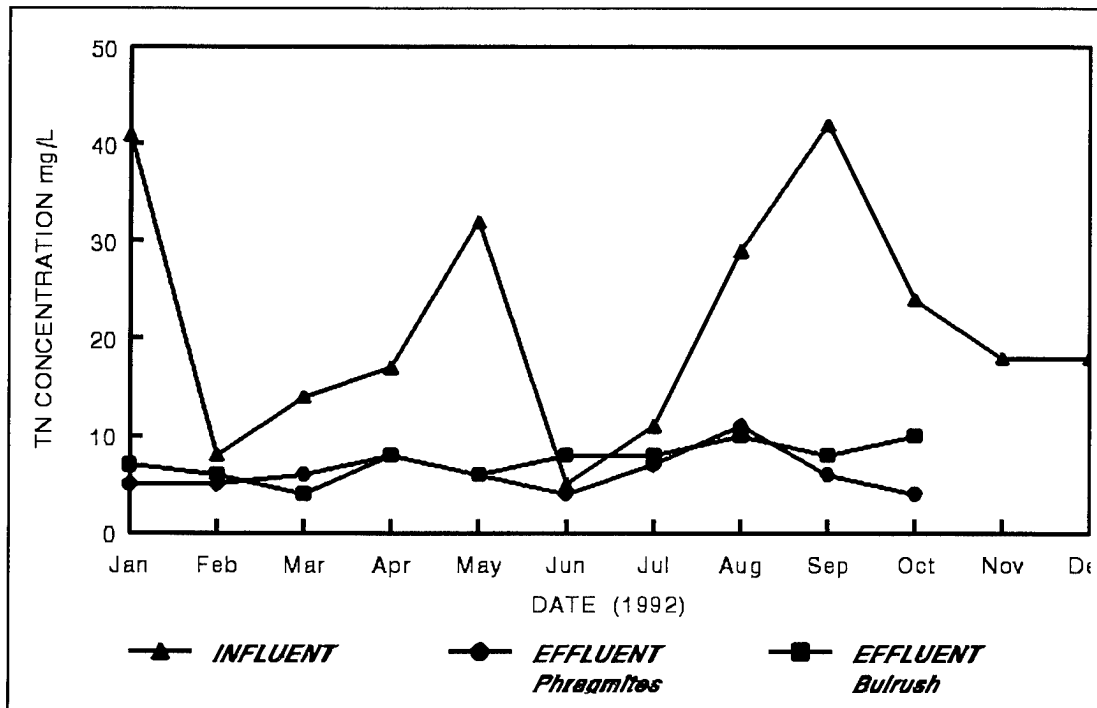


Figure 5. Nitrogen removal in constructed wetlands.

a lagoon in the coldest part of the winter. In these cases the winter water temperatures would be too low to sustain the nitrogen removal reactions and the wetland would also be at risk of complete freezing.

Design Considerations

Design procedures for removal of BOD, TSS, Nitrogen, Phosphorus, and fecal coliforms are available and can be found in Reed, Crites, and Middlebrooks (1995). The removals of BOD, nitrogen, and fecal coliforms are all temperature dependent processes. As a result, determining the water temperature in the wetland to achieve a proper design is necessary. This will vary with local site-specific conditions so a simplistic "rule of thumb" is not possible. Rational design procedures for this purpose are also available in Reed, Crites, and Middlebrooks (1995). Winter conditions in cold climates are critical. The system design must ensure that the necessary pollutant removal can occur at the low winter temperatures and that complete freezing does not occur in the system. The hydraulic design of the wetland is equally important to ensure that the water flows at the desired rate and in the desired direction and that the entire wetland bed is effectively used.

Treatment Wetlands in Arid Climates

An additional concern for constructed wetlands in arid climates is the high evapotranspiration rate and lack of precipitation during the summer months. On hot dry days, the evapotranspiration can remove more than 50 percent of the design flow. This results in an increase in the concentration of the dissolved contaminants in the wastewater, but also results in a compensating increase in detention time in the wetland.

The worst case for wetlands in arid climates occurs if evapotranspiration removes all of the water entering the wetland on a year-round basis. Then, the dissolved contaminants will accumulate in the sediments of the wetland and may reach toxic levels for the plants or wildlife. A famous example is the Kesterson Marsh in California. This natural wetland received agricultural drainage water that was high in dissolved selenium. All of the water entering the marsh would evaporate during the dry summer months. As a result, over a long time, the selenium concentrations in the sediments reached toxic levels for the ducks and other birds in the wetland, causing high mortality rates. This marsh had to be closed and drained to avoid further problems. No constructed wetland designed for wastewater treatment has shown any evidence of such a problem, primarily because the water in the wetland does not completely evaporate; either a surface discharge or seepage to the groundwater is allowed in the final portion of the system. Table 4 lists many examples of successfully operating treatment wetlands in arid climates in the United States.

Table 4. Successfully operating treatment wetlands in arid U.S. climates.

Location	Wetland Type	Design Flow	Area
Incline Village, NV	FWS	1.7 mgd,	122 acres treatment area, 387 acres total area.
ShowLow, AZ	FWS	design flow 1.4 mgd	201 acres treatment and seepage area.
Pinetop/Lakeside, AZ	FWS	2 mgd	127 acres treatment and seepage area.
Hotsprings, WY	FWS	110,000 gpd	1.55 acres
Capitan, NM	FWS	85,000 gpd	1.39 acres
Ouray, CO	FWS	363,000 gpd	2.2 acres
Mountain Shadows Health Care Center, Las Cruces, NM	SF	17,000 gpd	0.33 acres
La Siesta Retirement Center, Hobbs, NM	SF	6,000 gpd	0.11 acres
Public Service Co. of Colorado	SF	4,500 gpd	0.03 acres
Tablazon Subdivision, Cedar Crest, NM	SF	12,800 gpd	0.34 ac

These successful experiences suggest that a constructed wetland can also be designed for successful performance at the UTTR. All of the FWS systems on this list have very significant habitat values; the Pinetop and Showlow systems were designed specifically for this purpose.

Wetland Design for UTTR

The proposed system would retain the two modified existing RI basins as part of the process. A bentonite treatment would be used to at least partially seal the basin sides and bottom to induce a discharge and the resulting ponds would be operated as a facultative pond with two cells in series. The theoretical HRT at the present flow rate of 18,200 gpd would be about 32 days. At the possible 37,000 gpd future flow rate the HRT would be 16 days. Data are not available on the characteristics of the untreated wastewater. Assumed values for this wastewater, and calculated values for the lagoon effluent are given in Table 5.

The critical design parameter for many of these constructed wetland systems is the ammonia level in the effluent to meet increasingly stringent regulatory requirements. At this UTTR system, the critical design parameter for the wetland is obtaining sufficient BOD removal during the warm summer months to permit the landscape irrigation option with minimal additional treatment. Filtration and disinfection will be required for this option, but a wetland effluent with a BOD and TSS less than 10 mg/L would simplify these final treatment steps. Removal of BOD and TSS to these levels would not be required during the colder winter months since irrigation should not be necessary. Removal of nitrogen and phosphorus to low levels is not required for either of the reuse options since nutrients in the water will be desirable for the irrigation option, and would not have an adverse impact on the in-situ aquifer.

Table 5. Assumed UTTR wastewater and lagoon effluent characteristics.

Parameter	Concentration (at the 18,200 gpd present flow rate)		
	Raw Sewage	Lagoon Effluent	
		Summer	Winter
BOD ₅	250 mg/L	31 mg/L	154 mg/L
TSS	240 mg/L	85 mg/L	85 mg/L
NH ₃	25 mg/L	18 mg/L	25 mg/L
TN	40 mg/L	30 mg/L	30 mg/L
TP	8 mg/L	6 mg/L	6 mg/L
Fecal Coliforms	10 ⁶ /100 ml	22,000 /100 ml	300,000 /100 ml

As indicated previously, temperature, precipitation, and evaporation all influence the performance of a constructed wetland. A search was made of Utah weather records and the SaltAir Salt Plant at latitude N40:46, longitude W112:07 (at the southern end of the Great Salt Lake, about 20 miles east of UTTR) was selected as a representative data source. Table 6 summarizes pertinent data.

The next step in system design is to determine which type of wetland will best serve the needs at UTTR. The advantages of the SF type were described previously. However, several of these advantages are not a concern at UTTR, i.e., less public exposure, no mosquitoes, no odors, because of the remote nature of the site and routine limits on public access to the UTTR. The SF wetland also requires a smaller land area than the FWS type, but this feature is not critical at UTTR since an excess of land, at no cost, is available for this purpose. In addition, a source of appropriate gravel is not readily available—this would further increase the cost of the project. The SF concept does provide greater thermal protection during the cold winter months, but preliminary calculations show that the maximum ice depth on an FWS wetland during the coldest winter of record would be about 6 in. If the initial winter water depth is set at 2 ft, 1.5 ft of liquid treatment volume would still be available.* Since enhancement of wildlife habitat values is a major purpose of this project, an FWS wetland was selected for the treatment wetland in this project. The FWS wetland will also be less costly to build than an SF type. A SF wetland might be 1/2

Table 6. Climatic data for design of UTTR wetland.

Month	Average Temp. (°C)	Precipitation (in.)	Pan Evap.* (in.)	Net (in.)	Netx0.8 [†] (in.)
January	-7	0.71	1.9	- 1.2	- 1.0
February	-2	0.76	1.7	- 0.9	- 0.8
March	4	1.31	3.9	- 2.6	- 2.1
April	8	1.73	6.2	- 4.5	- 3.6
May	15	1.73	9.1	- 7.4	- 5.9
June	21	1.02	11.9	-10.9	- 8.7
July	24	0.68	14.4	-13.7	-11.0
August	24	0.78	12.7	-11.9	- 9.5
September	16	1.21	8.5	- 7.3	- 5.8
October	12	1.32	4.9	- 3.6	- 2.9
November	5	1.11	2.1	- 1.0	- 0.8
December	- 0.5	0.82	2.1	- 1.3	- 1.0
*Evaporation from a wetland is taken as 80 percent of pan evaporation.					

* 1 in. = 25.4 mm; 1 ft = 0.305 m.

to 2/3 the size of an FWS wetland depending on pollutant removal requirements, but the costs of the gravel media result in higher SF wetland construction costs. The SF wetland also has little habitat value since the water surface is not exposed.

As described previously, BOD is the limiting design parameter for this project. The wetland will therefore be sized to produce the desired levels of effluent BOD, using appropriate design models (Reed, Crites, and Middlebrooks 1995). The removal of BOD, TSS, nitrogen and phosphorus have been described with first order plug flow models. In addition, the removals of BOD and nitrogen are temperature dependent reactions. The basic models take the form:

$$\frac{C_e}{C_o} = \exp(-K_T t) \quad [\text{Eq 2}]$$

$$K_T = K_{20} (1.06)^{(T-20)} \quad [\text{Eq 3}]$$

$$K_{20} = 0.678 \text{ d}^{-1} \quad (\text{for BOD in FWS wetlands}) \quad [\text{Eq 4}]$$

For UTTR, use a 20 percent safety factor, so:

$$K_{20} = 0.542$$

The wetland surface area can be determined with Eq. 4:

$$A_s = \frac{Q \ln C_o - \ln C_e}{K_T (y) (n)} \quad [\text{Eq 5}]$$

where:

- A_s = bottom surface area of wetland, sq ft (1 sq ft = 0.093 m²)
- Q = design flow, cu ft/day (1 cu ft = 0.028 m³)
- C_o = influent concentration, mg/L
- C_e = effluent concentration, mg/L
- K_T = rate constant, at temperature T, d⁻¹
- y = design depth of water in the system, m
- n = "porosity" of the wetland, 0.65 to 0.75

For the initial case, it is assumed that it is desired to produce an effluent BOD of about 30 mg/L in the winter, with 0.4 ft of ice on the FWS wetland. The operational water depth would then be 1.6 ft. Based on the tabulated climate data and appropriate thermal calculations, the bulk water temperature in the wetland would be approximately 3°C. According to the data in Table 5, the influent BOD to the wetland would be 154 mg/L. Application of these data in Equation 4 will produce a required wetland area of about 15,000 sq ft, at the present flow rate of 18,200 gpd. That total area would be divided into two parallel cells, each about 50 ft wide and 150 ft long.

Having determined a potential wetland area, determining a water balance is then possible based on precipitation and evapotranspiration. Finally, actual total flow through the wetland and the expected performance monthly can be found. Figure 6 presents the expected wetland water temperatures during a full annual cycle. Figure 7 presents the variation in wetland water depth and detention time. Operating the wetland with a 2-ft water depth during the winter to provide sufficient detention time and an allowance for ice formation is necessary; a 1-ft depth in the summer months is more desirable for plant development and habitat values.

The expected effluent BOD, at the present flow rate, is shown in Figure 8 for a complete annual cycle. The wetland influent BOD ranges from 154 mg/L in the coldest part of the winter to 16 mg/L in the warmest part of the summer. The effluent BOD is shown on the figure at a steady 6 mg/L from May through September.

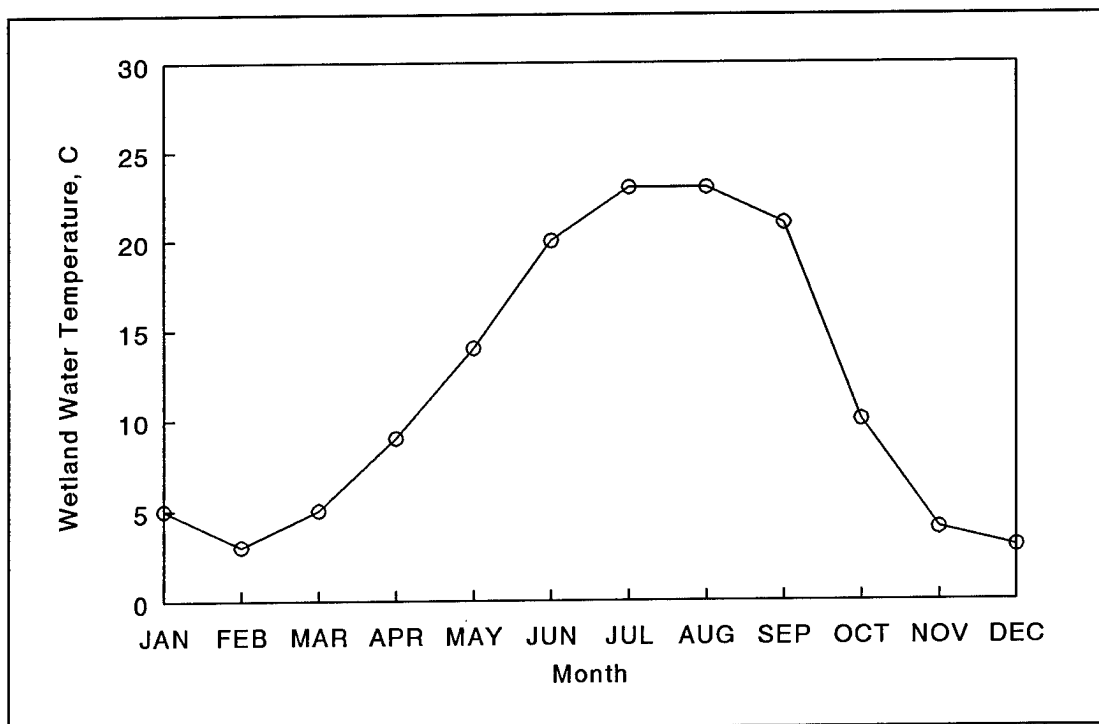


Figure 6. Expected water temperatures in the UTR treatment wetland.

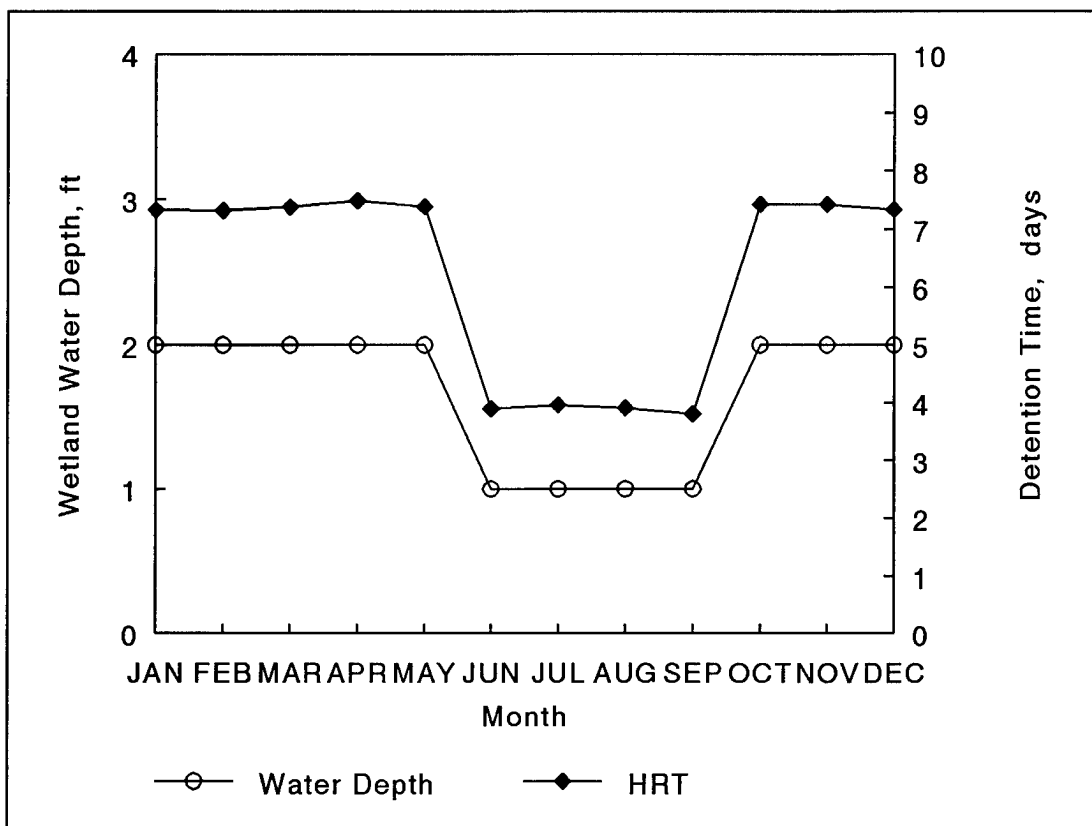


Figure 7. Water depth and HRT in the UTTR treatment wetland.

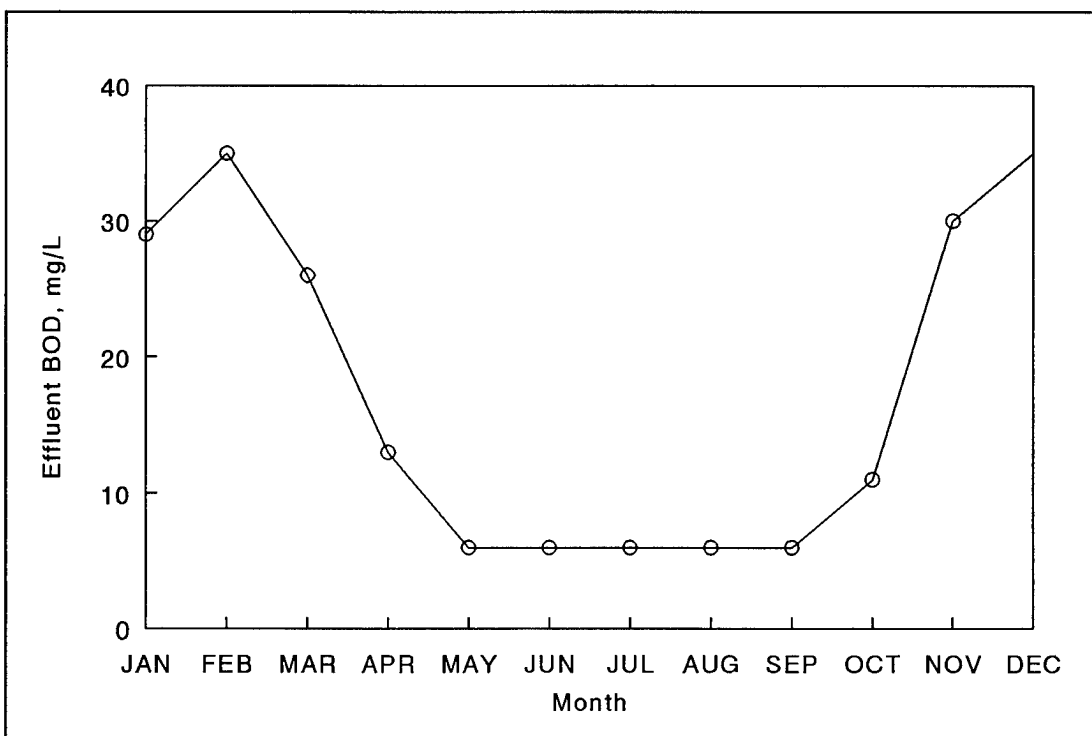


Figure 8. Predicted effluent BOD, UTTR treatment wetland.

A unique aspect of these wetland systems is that BOD is generated within the system by decomposition of the vegetation, and deposition of wastes from resident wildlife. The wetland removes essentially all of the wastewater BOD during the warm months; the effluent concentrations are this residual BOD, which can range from 2 to 7 mg/L.

The effluent BOD from mid-April to mid-September should be below 10 mg/L and therefore satisfy the Utah Type 1 reuse requirements for landscape irrigation. Such water is also more than suitable for enhancement of wildlife habitats. While the effluent BOD exceeds the 10 mg/L standard during the winter months, Type 1 irrigation usage is not a factor during this period. The essentially secondary effluent is better in quality than is now being disposed of in the present RI basins.

Figure 9 shows the expected TSS concentration in the wetland effluent over a full annual cycle. Removal of suspended solids in the wetland is largely a physical separation process that is not temperature dependent. There may be some seasonal variation in effluent solids from the lagoon due to variations in algal concentrations, but to be conservative, an annual influent concentration of 85 mg/L to the wetland was assumed. This results in an effluent of less than 10 mg/L. This is an excellent quality effluent, but filtration to meet the Utah Type 1 reuse requirements for landscape irrigation would still be necessary if this reuse option were selected.

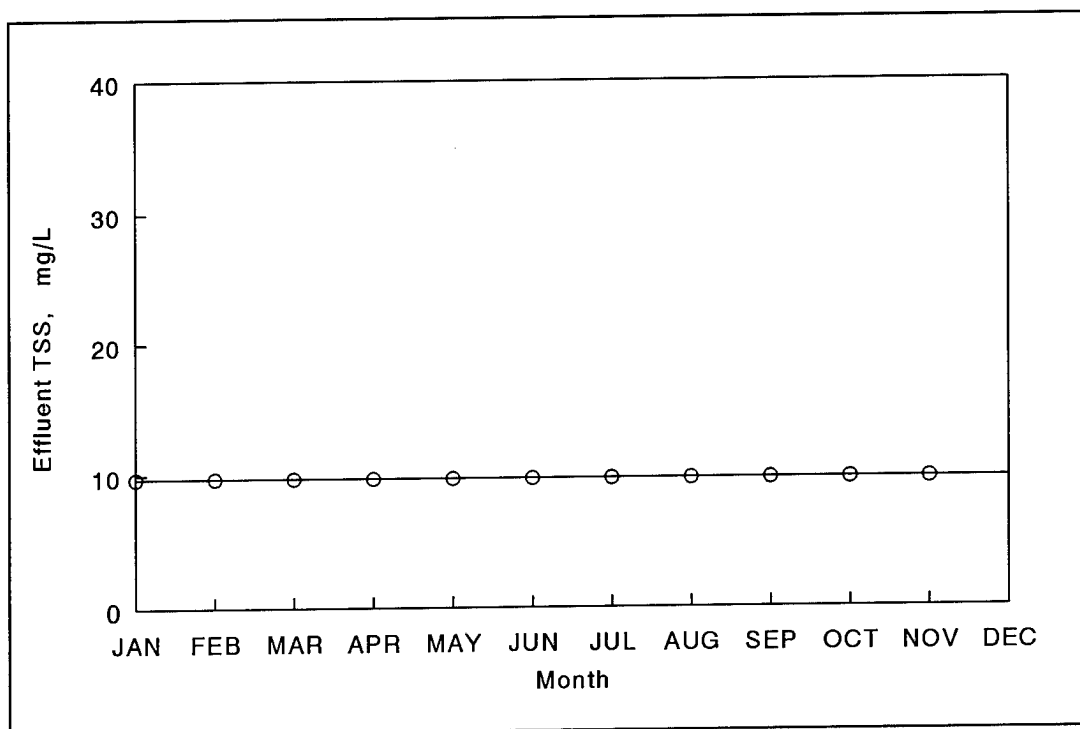


Figure 9. Predicted effluent TSS for the UTTR wetland.

Figure 10 presents the predicted effluent nitrogen concentration for the UTTR treatment wetland. At this site, nitrogen removal is not a critical design requirement since protection of surface or ground waters is not an issue. If the irrigation reuse option is selected, the presence of significant nitrogen in the effluent is a benefit.

Wetlands of both the FWS and SF types have limited capabilities for ammonia removal as compared with BOD and TSS. As shown in Figure 7, the HRT in this wetland ranges from about 7 days in the winter to about 2.5 days in the warm summer months. That is more than adequate to achieve excellent removal of BOD and TSS, but is not adequate to produce low levels of ammonia. Summer detention times of about 12 days or more would be required to achieve very low (<5 mg/L) ammonia concentrations, which is often required for discharge to surface streams where toxicity is a concern.

Seasonal variations in nitrogen concentrations leaving the facultative pond unit will occur, but to be conservative, a constant year-round concentration of 30 mg/L TN has been assumed. The variations in effluent concentration are then due to the temperature differences, and the seasonal changes in flow, water depth, and detention time.

Figure 11 shows the expected effluent phosphorus concentrations. This is based on an assumed 6 mg/L leaving the facultative lagoon. The actual wetland system may experience some seasonal variation in phosphorus concentrations, but the available design model can only predict an annual average value; in this case, 3 mg/L.

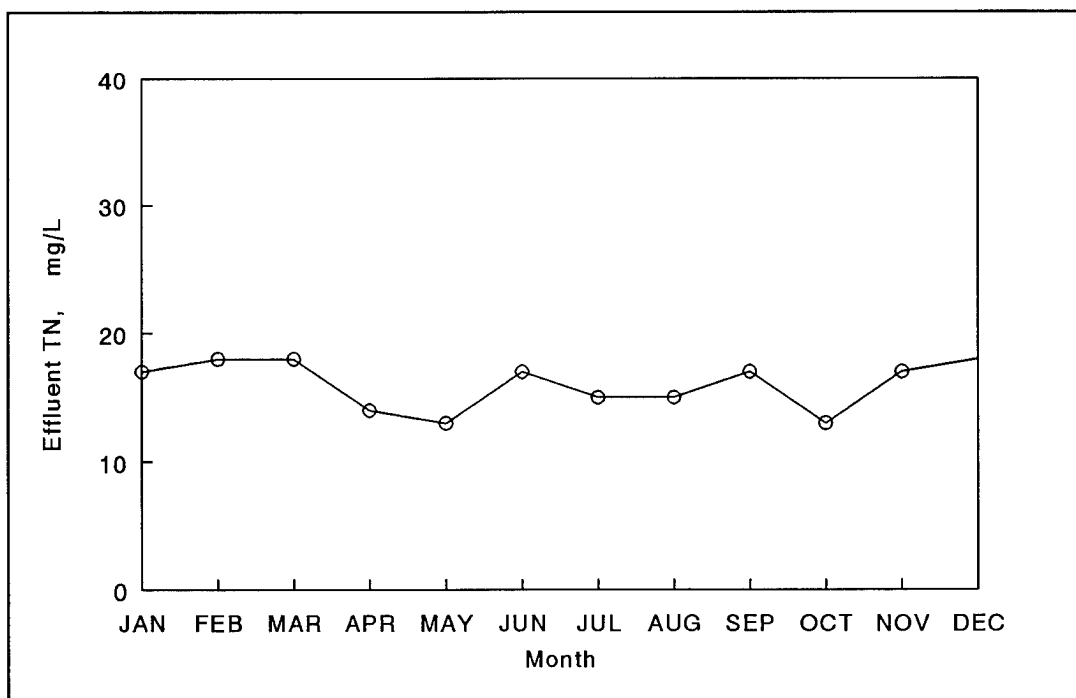


Figure 10. Predicted effluent nitrogen concentrations, UTTR wetland.

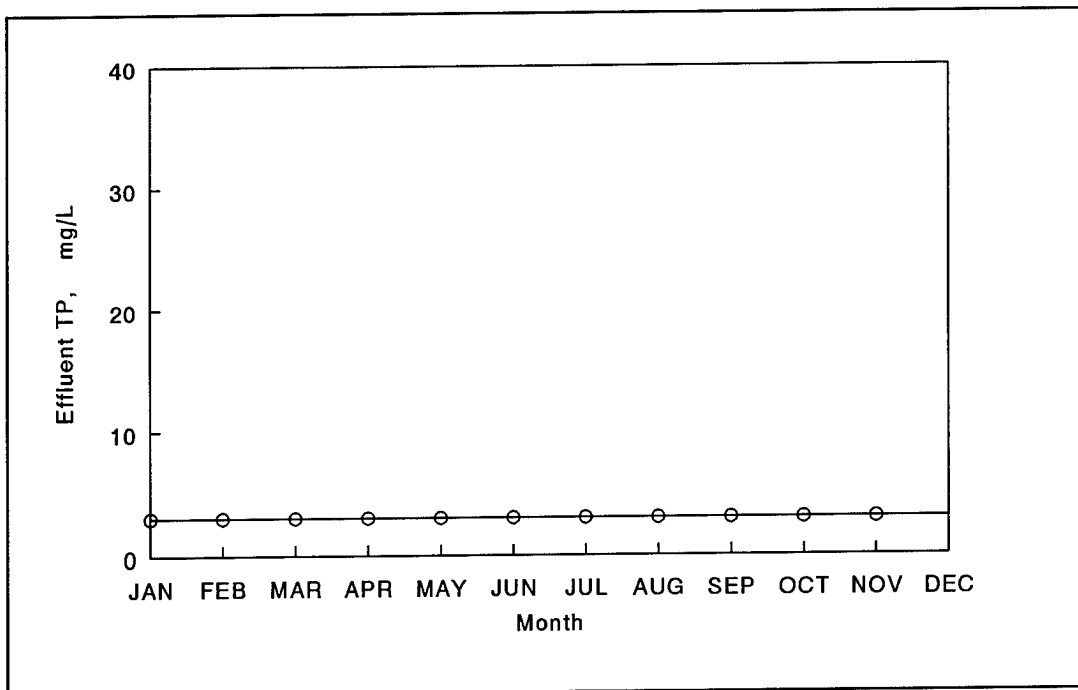


Figure 11. Predicted effluent phosphorus concentration, UTTR wetland.

Figure 12 presents the expected fecal coliform concentrations in the treatment wetland effluent. The wetland influent values will vary seasonally because of temperature influences on the facultative pond. The influent concentrations will range from 338,000/100 mL in the winter months, to 22,000 /100 mL in the warmest part of the summer. The wetland effluent values are also dependent on temperature

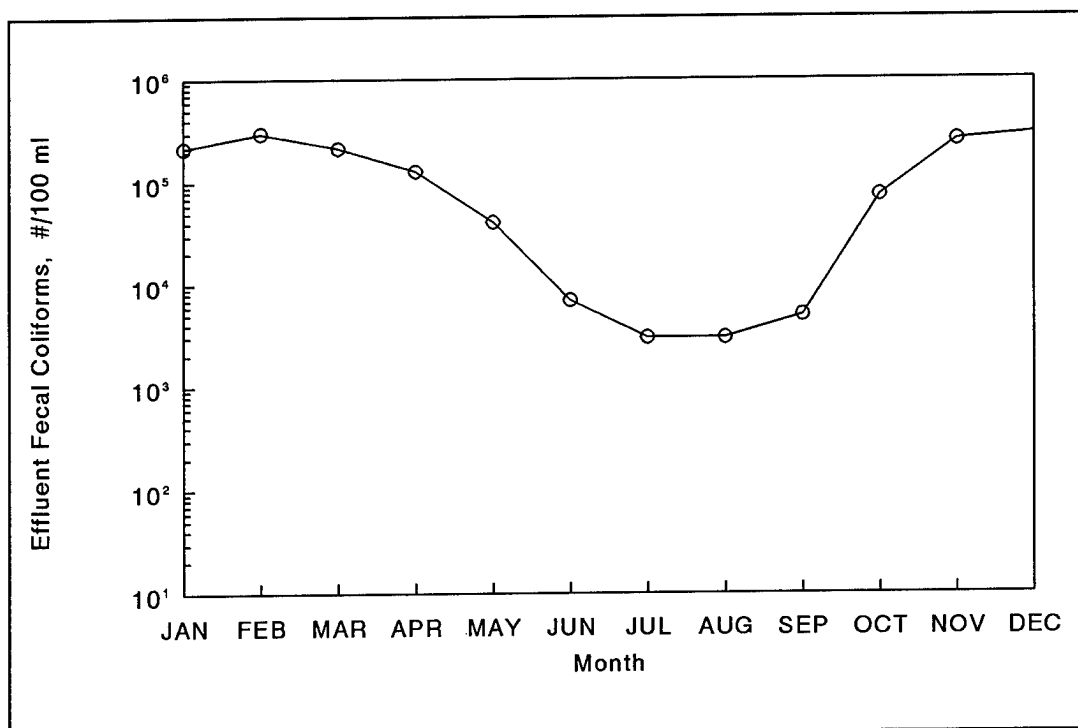


Figure 12. Effluent fecal coliform concentrations, UTTR wetland.

and on detention time in the wetland. Maintaining the wetland water depth at 2 ft during the summer months might reduce the fecal coliforms to less than 2000 /100 mL so the improvement would be marginal. Filtration and disinfection would still be required for the irrigation reuse option. Selection of suitable filtration and disinfection equipment is beyond the scope of this report. Since the State of Utah requires a chlorine residual in Type 1 reuse water, the type of disinfection used is not optional.

Figure 13 shows the response, for BOD, if the flow rate does increase to the possible 37,000 gpd level. The curve labeled "two cell" represents the response if the 37,000 gpd flow were applied to the presently proposed two cell wetland. Here the BOD would be below 30 mg/L from April through mid-September and should still be suitable after filtration for Type 1 irrigation reuse. The higher winter BOD values would still be compatible with in-ground disposal in the final modified overflow basin. The curve labeled "three cell" illustrates the response if a third, equal sized, cell were added to the wetland. This would yield some obvious improvement in performance, but not enough to change the reuse opportunities significantly.

Wetland effluent water quality will obviously deteriorate if the flow rate ever increases to 37,000 gpd, but that change may not affect either of the reuse options under consideration. An alternative to adding a third cell or to doubling the size of the wetland if the flow rate increases would be to add aeration capacity to the first

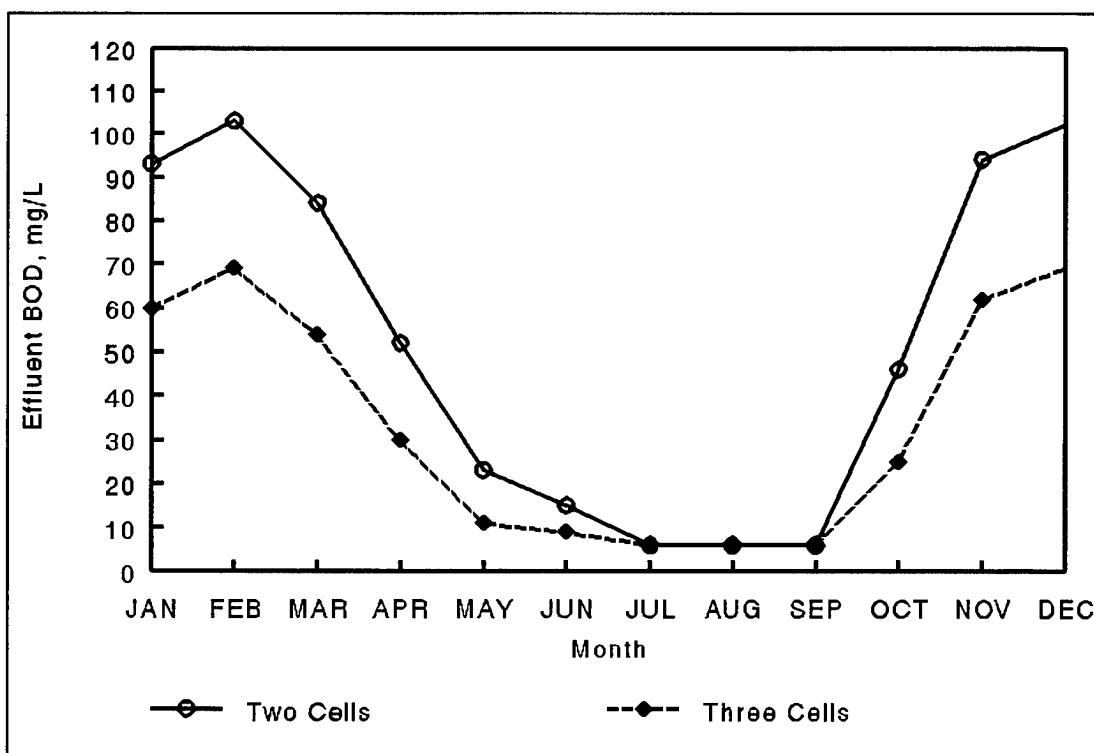


Figure 13. Effluent BOD at 37,000 gpd in a two and a three cell wetland.

cell of the lagoon. This would significantly reduce the BOD concentration at that point in the system. Based on discussions with Hill AFB personnel, it appears unlikely that the flow rate will ever increase to the 37,000 gpd level.

Wetland System Costs

Table 7 lists the preliminary estimated costs for the modifications to the UTTR system. These are the costs for the wetland habitat reuse option only. The costs for the landscape irrigation reuse option are beyond the scope of this report and are not included. These costs cannot be determined until the areas for landscape irrigation, and the irrigation methods to be used are identified. This irrigation reuse option would require all of the system components discussed previously plus a pump station after the FWS treatment wetland to return treated effluent to the built-up portion of UTTR. A storage tank, filtration equipment, another distribution pump, and appropriate distribution piping would also be required. These components will add significantly to the costs and the operational complexity of this reuse option.

Table 7. Preliminary estimated costs for wetland modifications at UTTR.

Item	Cost
Lagoon sealing, w/bentonite	\$ 3,875
Flow splitter to wetland	\$ 2,819
Misc. pipe and fittings	\$ 3,681
Construct FWS treatment wetland w/bentonite liner	\$ 20,137
Water level control for wetland	\$ 1,690
Construct habitat wetland/pond w/bentonite liner for wetland plastic liner for pond	\$ 3,266
Subtotal	\$ 35,468
Overhead & profit	\$ 7,362
Engineering & Admin.	\$ 8,000
Contingencies	\$ 3,547
Total	\$ 54,377

Design Specifications

USACERL provided Hill Air Force Base with design drawings and construction specifications to implement the water reuse concept. Figure 14 shows an existing system and an added constructed wetland system. Figure 15 shows a system profile. Figure 16 and 17 show cross sections of constructed wetland systems.

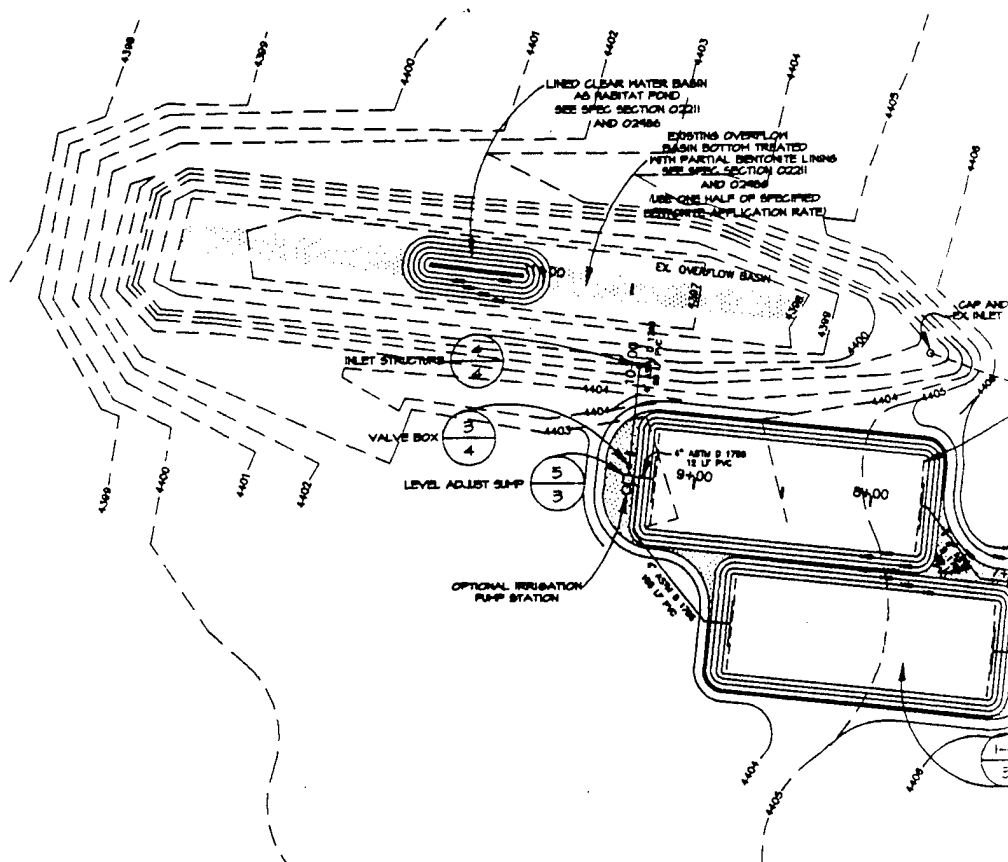
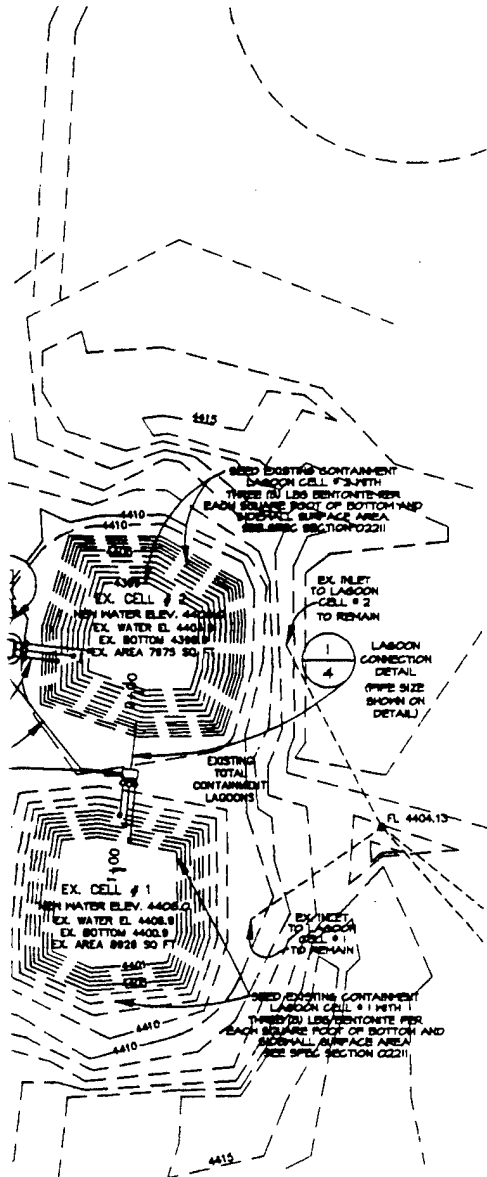


Figure 14. Site plan.

①



UTAH TEST AND TRAINING RANGE HILL AIR FORCE BASE, UTAH ONSITE WASTEWATER TREATMENT & REUSE

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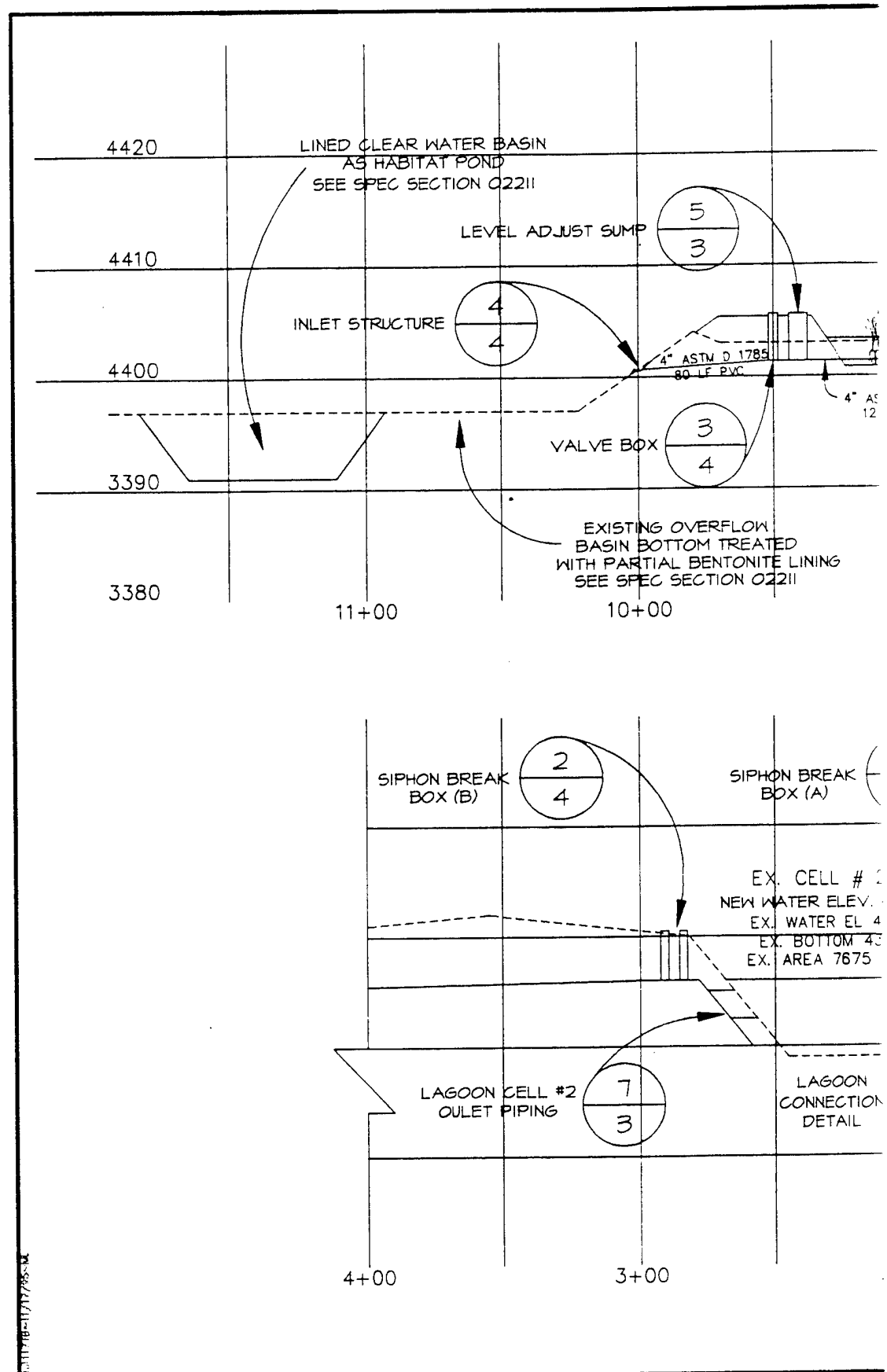
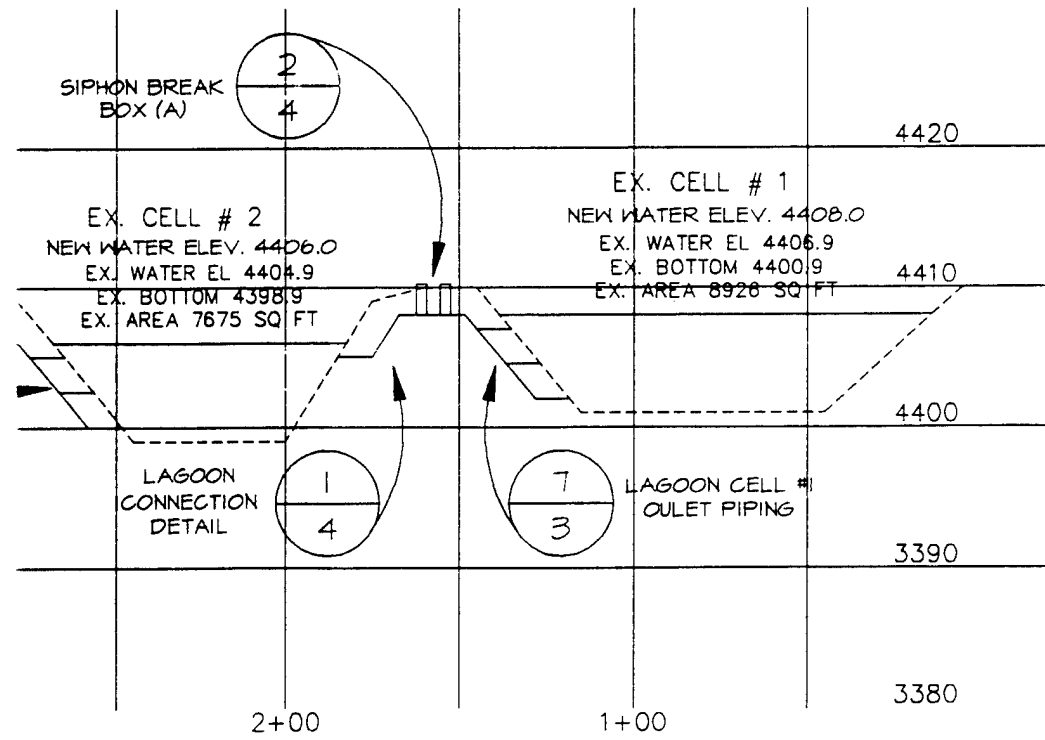
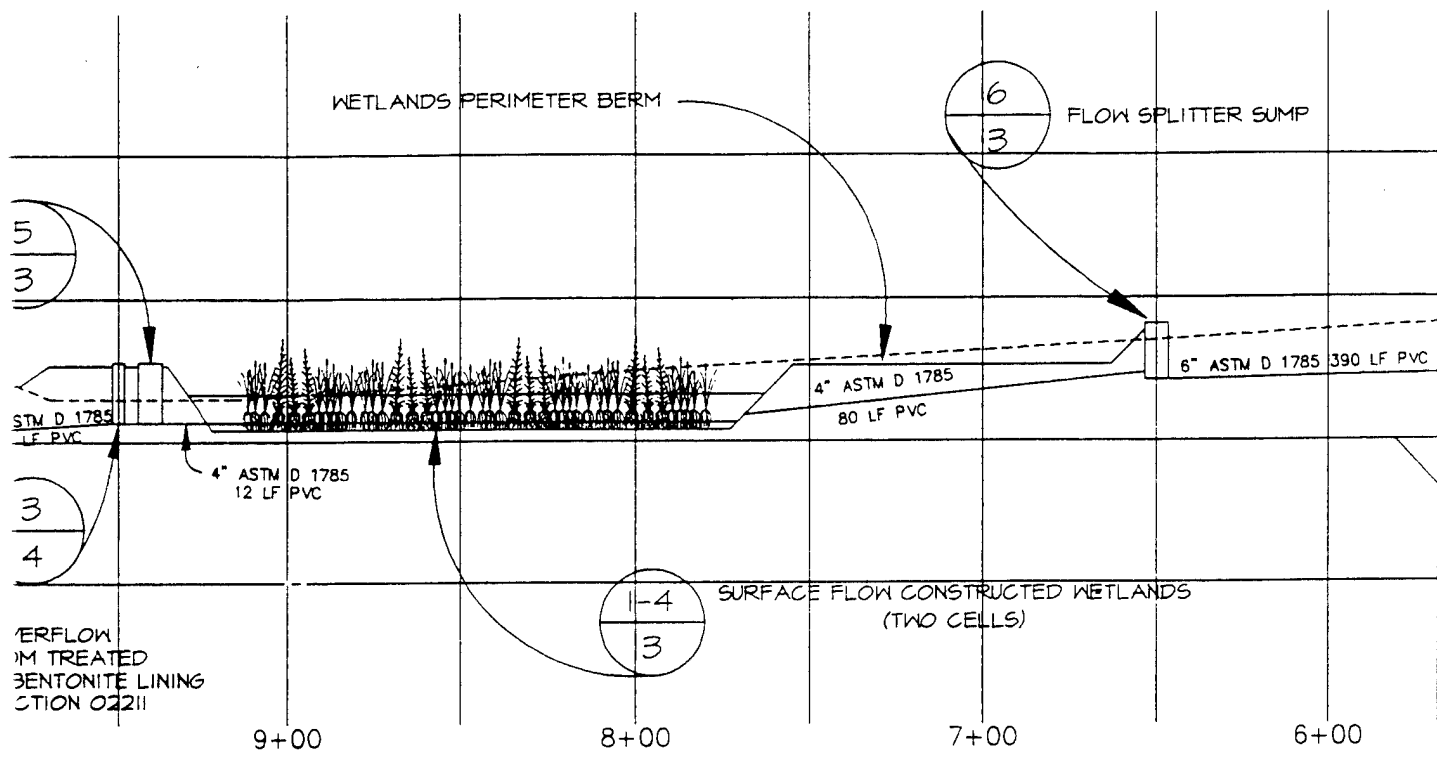


Figure 15. System profile.



2

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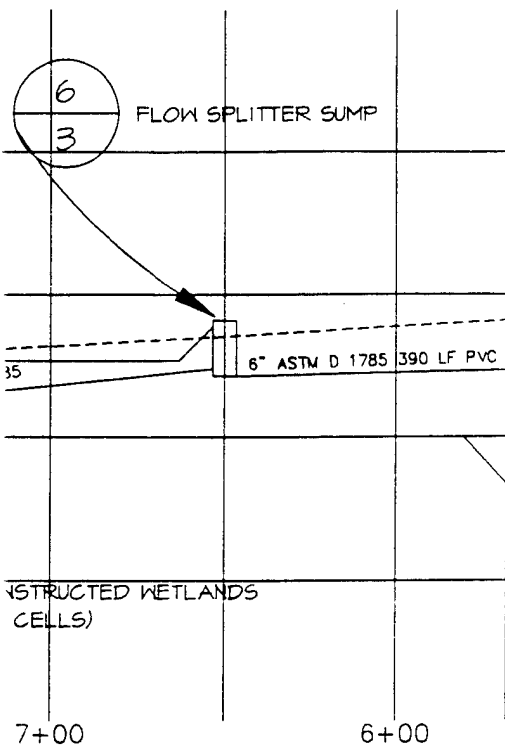
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HILL AIR FORCE BASE, UTAH
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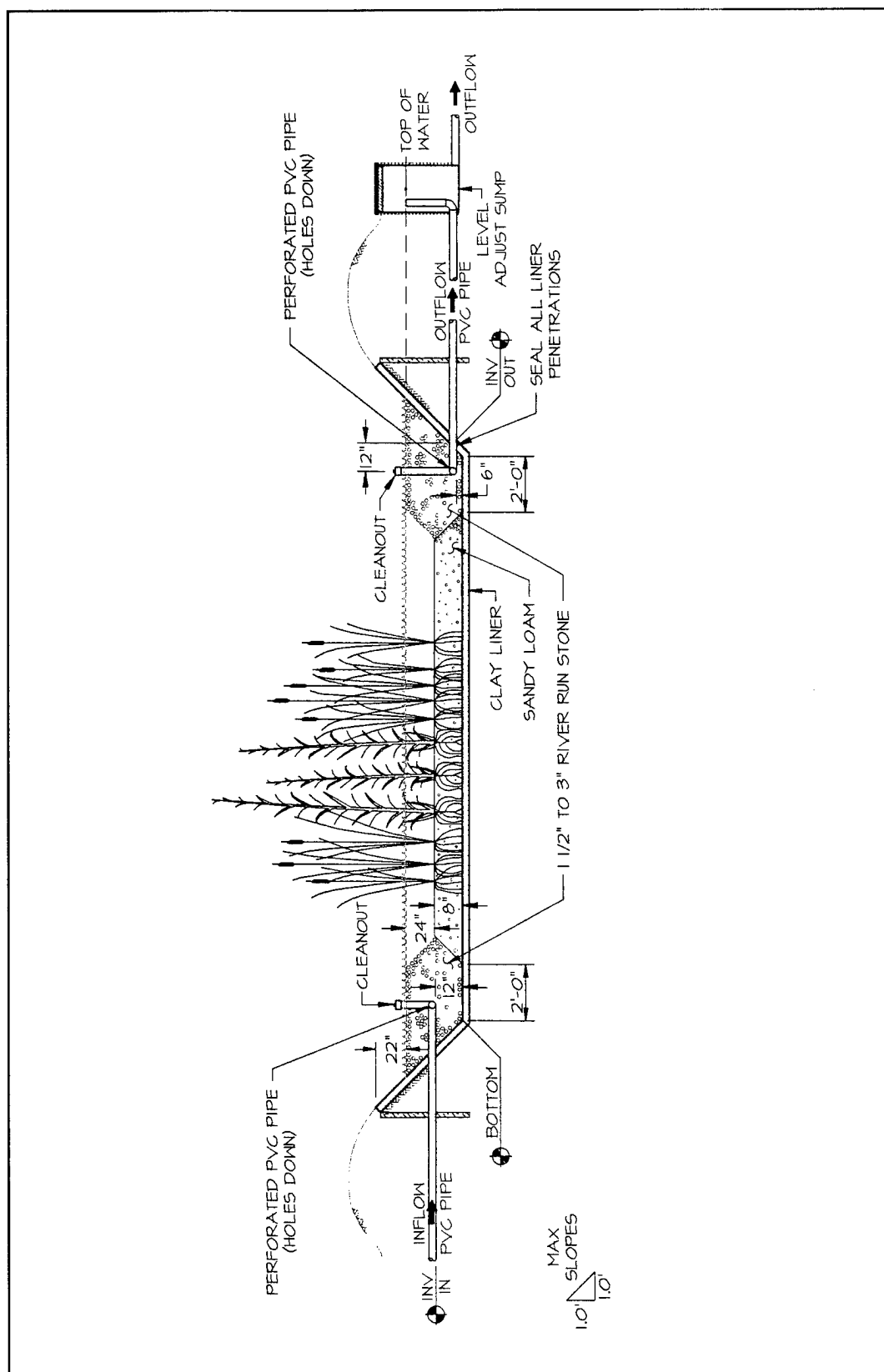
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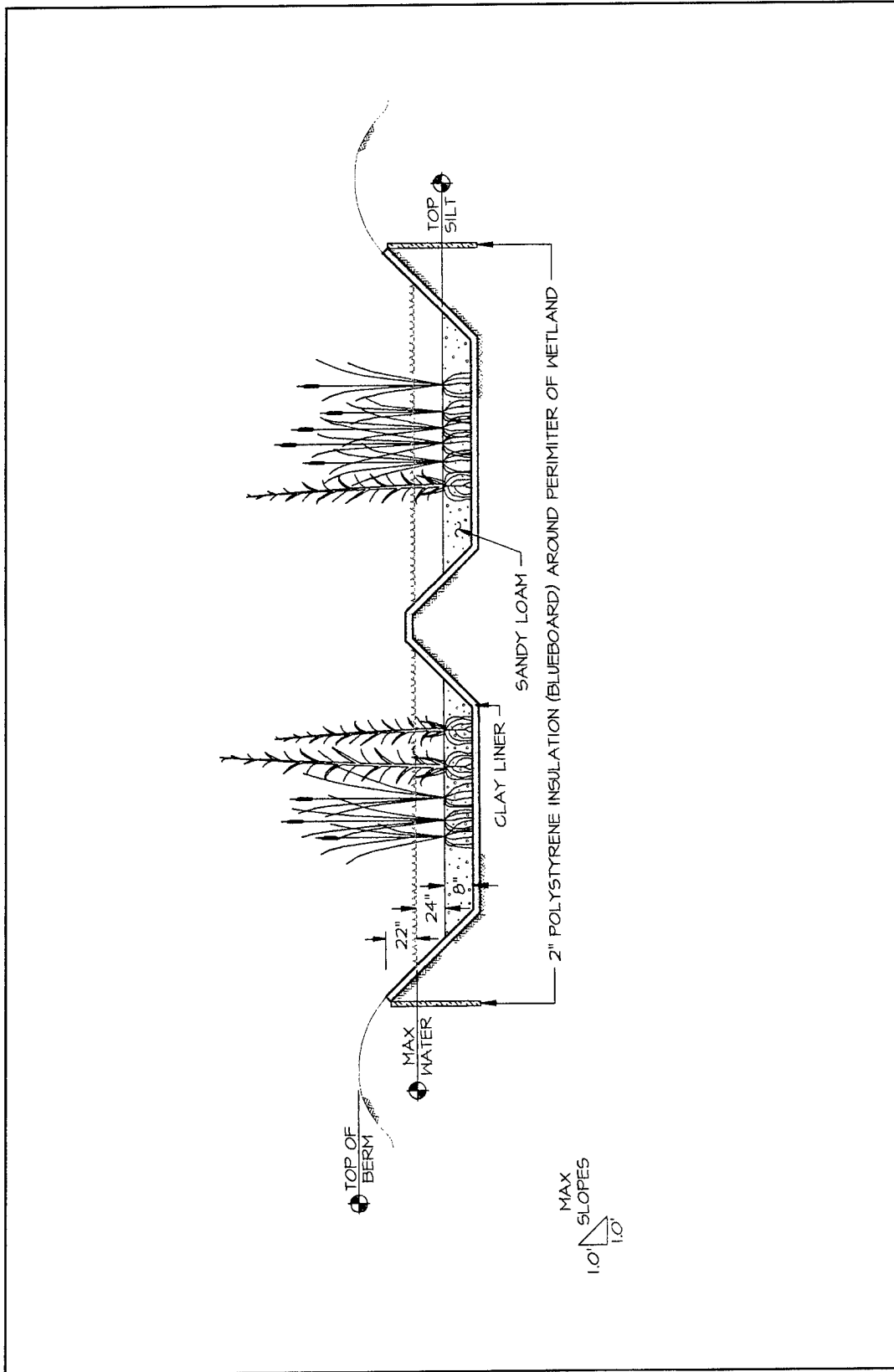


Figure 17. Cross section of wetland system.

4 Conclusions and Recommendations

Conclusions

This study evaluated the design and function of the wastewater treatment and disposal facilities at the Utah Test and Training Range, Hill AFB, UT, and concludes that:

1. No technical or regulatory basis exists for replacement or modification of the present rapid infiltration basin disposal practice at the UTTR. The present RI basins have apparently performed adequately for many years and should continue to do so for the future. It is believed that the existing emergency overflow basin has the capacity to receive and dispose of excess flow if the UTTR flow rate ever increased to 37,000 gpd from the present 18,000 gpd. This capacity could be confirmed with additional infiltration testing in the bottom of this overflow basin. If it proves inadequate, it could easily be enlarged with available on-site equipment. The only other concern with the present operation is the potential accumulation of sludge in the two RI basins. It is recommended that the depth of sludge be measured annually, and the rate of increase be determined. At some point in the future, removing this accumulated sludge may be necessary to allow the bottom of each RI basin to dry, to restore infiltration capacity.
2. There is an environmental basis to consider modifying the system with a constructed wetland for additional treatment and reuse of that water. Such reuse would enhance wildlife and bird habitats and could also provide landscape irrigation at the built-up portion of UTTR. Both the FWS treatment wetland and the conversion of the existing emergency overflow basin to a wetland/pool would provide a significant area of green vegetation at UTTR throughout the warm months of the year. This vegetation and the exposed water surfaces would provide significant habitat values for animals and birds. This portion of the system would be almost completely passive and would not require frequent operational or maintenance attention, only a semiannual adjustment in treatment wetland water depth. If landscape irrigation is also wanted, an optional pump station can be sited after the treatment wetland to return most of the treated effluent to the built-up part of UTTR.

3. The landscape irrigation reuse option is not a passive system. Based on discussions with officials from the State of Utah, the system would be classified as a Type 1 reuse activity and would require filtration, disinfection, maintenance of residual chlorine, and routine water quality monitoring. All these activities would significantly increase the operational and maintenance requirements as compared with the present system, or the passive wetland modification. Construction of a treatment wetland and retention of the existing overflow basin would still be necessary for this option, and the total construction costs would increase significantly for the pumps, distribution piping, storage tank, filtration, and disinfection units required.

Recommendations

This study recommends that:

1. Before any commitment to the landscape irrigation option a cost comparison should be made between wastewater reuse as defined in conclusion 3 above and the costs of an increase in fresh water production via the present RO process for this purpose. Landscape irrigation with water from the present RO process would not need the filtration, disinfection, or the monitoring required if treated wastewater is used for this purpose.
2. It is recommended that suitable valving and piping be installed ahead of the two existing RI basins to permit their operation either in series or parallel in the proposed conversion.
3. It is also recommended that Hill AFB base its implementation of the water reuse concept on the USACERL-provided design drawings and construction specifications.

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